

The SNO+ experiment: status and overview

José Maneira for the SNO+ Collaboration

LIP, Av. Elias Garcia 14, 1st, 1000-149 Lisboa, Portugal

E-mail: maneira@lip.pt

Abstract. SNO+ is a multi-purpose Neutrino Physics experiment, succeeding to the Sudbury Neutrino Observatory by replacing heavy water with liquid scintillator. Its scientific goals are the search for neutrinoless double-beta decay, the study of solar neutrinos and antineutrinos from reactors and the Earth's natural radioactivity, as well as supernovae neutrinos. The experimental advantages of SNO+ are the possibility of loading large quantities of double-beta decaying isotope in the liquid scintillator volume, and the very low backgrounds allowed by the deep underground location and radiopurity of the employed materials. The installation of the detector at SNOLAB is being completed, and commissioning has already started, with a dry run. Filling with water and later, with scintillator, will start next year. This talk will summarize the Physics goals of SNO+, as well as the main detector developments.

1. Introduction

SNO+ [1] is a multi-purpose experiment for low-energy neutrino physics. The Sudbury Neutrino Observatory detector [2], located deep underground at SNOLAB[3], will be re-used with liquid scintillator instead of heavy water, allowing several Physics goals, from neutrinoless double beta decay searches, to measurements in with several sources of low energy neutrinos – the Sun, the Earth, Supernovae, and neighboring nuclear reactors.

SNO+ (see Fig. 1) is constituted by a 12 diameter acrylic vessel (AV) containing about 800 tonnes of liquid scintillator. A geodesical structure (PSUP) supports about 9500 8-inch diameter photomultiplier tubes (PMTs) coupled to a set of reflectors that increase the geometrical coverage to 55% of 4π . The AV and the PSUP are immersed in 7000 tonnes of ultra-pure water, that shield the scintillator volume of neutrons and gamma radiation from radioactivity in the PMTs and the surrounding rock. A thick liner prevents diffusion of Radon from the rock into the water volume. The deep underground location reduces the cosmic ray muon flux to about 70 per day.

These exceptional shielding properties give SNO+ the necessary conditions to carry out low background measurements at low energies. Neutrinoless double beta decay searches can be carried out with very low backgrounds from external materials, by simply reconstructing the event position and defining a fiducial volume. This is in fact one of the advantages of the liquid scintillation technique, in addition to the possibility of using large masses and performing in-situ purification, to reduce the backgrounds from the scintillator mixture itself.

For solar neutrinos, the low cosmic ray muon flux leads to a low rate of cosmogenic backgrounds, such as ^{11}C , that would otherwise disturb the measurements of the pep and CNO fluxes.



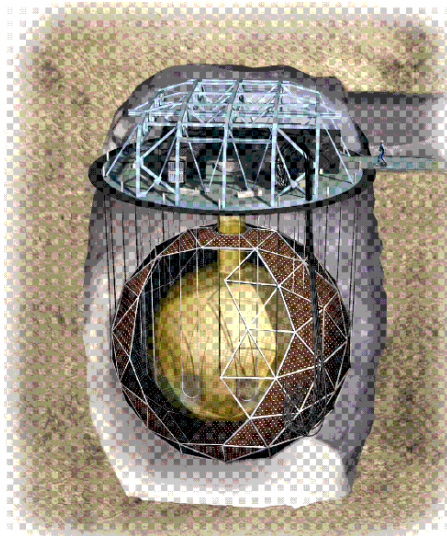


Figure 1. Artistic view of the SNO detector. SNO+ has an additional rope system holding the acrylic vessel down, anchored to the bottom of the cavity.

The Physics goals of SNO+ are presented in Section 2 and the detector changes and upgrades that have been developed are described in Section 3.

2. Physics goals

2.1. Neutrinoless Double Beta Decay

Neutrino Physics has made many progresses in the last decade and a half, with the discovery of neutrino oscillations. However, the issue of whether the neutrino is a Dirac or Majorana particle, of great importance for leptogenesis and Grand Unification theories [4], is still not solved. The search for neutrinoless double beta-decay (NLDBD) aims at answering this question and, in the case of the Majorana hypothesis, measuring the absolute value of the neutrino mass.

Large volume liquid-scintillator (LS) experiments SNO+ and KamLAND-Zen[5] have recently joined the competitive field of NLDBD. This type of detectors has two important advantages for NLDBD searches: a large isotope mass can be sampled, and very low backgrounds can be achieved for high Q-value isotopes. Purification of the scintillator and the isotope compound can effectively remove many contaminants of the scintillator itself, and cosmogenic isotopes produced by cosmic ray activation of the DBD isotope. Analysis techniques allow the rejection of events originating from radioactivity outside of the scintillator volume, by defining a fiducial volume; the internal backgrounds from the ^{238}U and ^{232}Th natural radioactivity chains that populate the energy region above 2 MeV can be tagged through delayed coincidences.

SNO+ has studied extensively the loading of Neodymium in the LAB (linear alkyl-benzene) liquid scintillator. The double beta decay isotope ^{150}Nd has the advantages of a large (calculated) phase space and nuclear matrix element (NME) for neutrinoless double beta decay[6], and a high Q-value of 3.37 MeV, above most natural radioactivity backgrounds. The LAB-Nd solution has been demonstrated to be stable for over 3 years, and many of its cosmogenically produced contaminants can be removed by purification. The isotopes ^{144}Nd , ^{176}Lu , ^{138}La , associated with the Neodymium compound, are expected to be present. The Q-value of their decays is low, far from the 3.37 MeV region, but the expected rate is high enough, above the two-neutrino signal, for pile-up events to reach the ^{150}Nd region. These will not be a concern, though, since analysis techniques have demonstrated to identify the pile-up events with high efficiency.

Optical attenuation is a limiting factor for the usable concentration. With the present measurements of optical properties and Monte Carlo simulations, the optimal loading for best sensitivity with natural Neodymium should be about 0.3%. Assuming a NME of 2.5 (IBM-2

model), a phase space factor of $2.69 \times 10^{-13} \text{yr}^{-1}$, a 50% fiducial volume and 80% livetime, a sensitivity of 110 meV is expected after 4 years of data-taking, as shown in Figure 2.

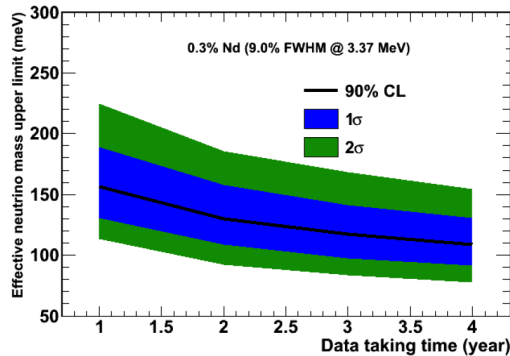


Figure 2. Expected sensitivity in effective neutrino mass from the ^{150}Nd neutrinoless double beta decay search in SNO+, with a 0.3% loading of natural Neodymium.

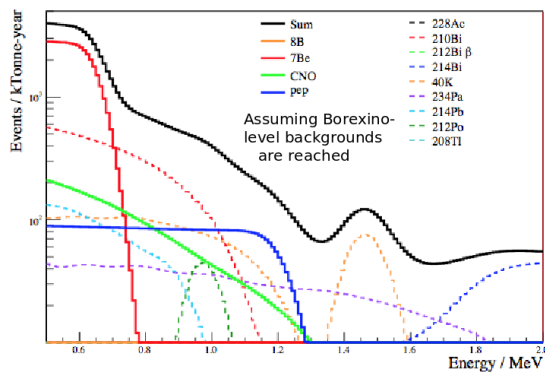


Figure 3. Expected signals from solar neutrino events and backgrounds, excluding ^{11}C (lower than the pep signal).

2.2. Solar neutrinos

The solar neutrino fluxes of ^8B , ^7Be and pep have been measured by SNO, Super-Kamiokande and Borexino (in addition to the integral measurements by the radiochemical experiments). However, a measurement of CNO neutrinos would be quite valuable to Solar Physics, as it could solve the "so-called" solar metallicity problem [13]. In addition, a precise measurement of the pep solar neutrino flux can confirm the predictions of the MSW oscillation mechanism in the vacuum-matter transition region and be sensitive to new Physics models [7].

Figure 3 shows the expected signals and main backgrounds in the intermediate energy range, from Monte Carlo simulations under the assumption that SNO+ reaches the same background levels as Borexino [14]. A joint maximum-likelihood fit was applied to these spectra, in order to estimate the expected precision, and the results are in Table 1. For pp and CNO neutrinos, these are still very rough estimations, since the backgrounds are harder to control and estimate in these cases.

SNO+ has a very strong advantage for these measurements. Cosmic ray muons interaction in the scintillator produce the ^{11}C isotope, that has an energy spectrum covering the pep and CNO neutrino region. Borexino has employed delayed coincidence techniques to reduce this background, with a severe loss of efficiency. In SNO+, depth alone would reduce the ^{11}C background by two orders of magnitude with respect to Borexino.

However, there is a possible additional background to consider in SNO+. Radon daughters have accumulated on the surface of the AV over the last few years in a significant way. If these leach into the scintillator, the purification system has the capability to remove them. However, depending on the actual leach rate, that removal might be inefficient and the ^{210}Bi levels in the scintillator too high for a pep/CNO solar neutrino measurement without further mitigation. Mitigation could include enhancing online scintillator purification, draining the detector and sanding the AV surface to remove radon daughters, or deploying a bag. Double beta decay, which is the priority of SNO+, and low-energy ^8B solar neutrino measurements are not affected by these backgrounds.

Flux	One year	Two years
pep	9.1%	6.5%
8B	7.5 %	5.4%
7Be	4%	2.8%
pp	a few % ?	
CNO	~ 15 % ?	

Table 1. Expected uncertainties on the SNO+ measurements of different solar neutrino fluxes, assuming Borexino level backgrounds are reached. Expectations for pp and CNO are highly dependant on the actual levels of backgrounds achieved, especially ^{14}C , ^{85}Kr and ^{210}Bi .

2.3. Reactor and geo-neutrinos

As in previous liquid scintillator experiments (Borexino and KamLAND), SNO+ can also detect antineutrinos from nuclear reactors through the inverse beta decay (IBD) reaction on protons, with a very small background due to the delayed coincidence tag between the positron and neutron signals. The region centered in Sudbury has a smaller number of nuclear reactors than the region of the Kamioka laboratory in Japan, so the expected flux of reactor antineutrinos in SNO+ is about 5 times smaller than the flux observed in KamLAND (before the Fukushima accident). However, the antineutrinos come predominantly from three reactor complexes. The closest one, in the Bruce peninsula, is at a distance of 281 km, and the next ones are close to Toronto, at distances of 330 km and 340 km. The effect of having almost only two baselines, results in a distinctive spectrum, with oscillation minima clearly visible (see Fig. 4), in contrast with the observed energy spectrum of detected antineutrinos in KamLAND. The sensitivity to the neutrino oscillation parameters is then expected to be similar to KamLAND after 3 years of data-taking, even with a significantly smaller flux.

The question of how much of the Earth's heat production is radiogenic is still a largely open one, and it depends, among other factors, on the amounts and distribution of the natural radioactivity isotopes of Uranium, Thorium and Potassium in the Earth [12]. Geo-neutrino measurements can provide some constraints on the problem, but they would have a stronger impact if a separation between the flux originating in the crust (closer to the detectors) or the mantle (more important for Geo-Physics) could be achieved [9, 11]. The thick continental crust (the "Canadian shield") where SNO+ is located gives a strong contribution to the estimated 20 events per year (including efficiencies), but this will be estimated by detailed geological surveys and calculations that are being carried out [12], so that the mantle flux can be obtained by subtraction from the total flux. In addition, the smaller reactor neutrino flux is an advantage for the detection of geo-neutrinos in SNO+ [10].

During the double-beta decay, we expect the delayed coincidence tag to be effective in identifying the antineutrino signal even in the presence of a large signal from the two-neutrino decay. So, even if with a reduced sensitivity with respect to the unloaded scintillator, due to worse energy resolution, reactor and geo-neutrino measurements will be possible during all phases of SNO+.

2.4. Neutrinos from Supernovae

SNO+ will also have good capabilities as a detector for Supernovae neutrinos. About 370 events are expected from a 3×10^{53} erg Supernova at a distance of 10 kParsec, from reactions of IBD on protons, elastic scattering on electrons, and reactions on Carbon nuclei. The dominant process is IBD, sensitive only to electron antineutrinos, but the neutral current reaction on ^{12}C should provide an interesting measurement of the total flux in all flavors. An additional 270 events are

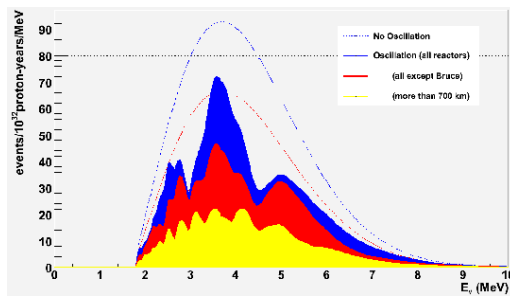


Figure 4. Expected energy spectrum of reactor antineutrinos at SNO+, from different reactor sources.

expected from elastic scattering on protons, with a smaller visible energy.

As in SNO, a careful design of calibration hardware and operational procedures should allow a semi-automated response to event bursts, so that SNO+ will be expected to participate in the Supernova Early Warning System (SNEWS).

3. Experimental developments

Converting SNO into a liquid scintillator detector is a complex undertaking, touching several experimental aspects, from mechanical to chemical issues, as well as calibrations, electronics, and software.

3.1. Liquid scintillator

The initial R&D program for SNO+ started with the identification of the liquid scintillator, that had to fill several performance requirements – high light yield, fast decay time – as well as safety requirements (due to the lab location in a mine), and also chemical compatibility with acrylic. Linear alkyl-benzene (LAB) was found to fulfill all the needed requirements, and in fact since then other experiments, such as Daya Bay, have used it.

The LAB scintillator can be efficiently purified, and the SNO+ online purification systems employs basically the same techniques developed by the Borexino experiment for the PC scintillator[14]: gas stripping, distillation, water extraction. Due to the SNOLAB logistics constraints, the SNO+ gas stripping will use water vapour instead of Nitrogen. The purification systems for SNO+ are presently being constructed and installed at SNOLAB.

3.2. Detector

The LAB scintillator has a density of 0.86, so the AV must take up a large buoyant force, as opposed to the downward force in effect when heavy water was used. This force is compensated by a new hold-down rope system, to be mounted over the whole AV, and secured at the floor of the experimental cavity. Detailed finite element analyses were carried out in the design phase. The material (tensylon) was selected due to its good radiopurity, and the existing hold-up ropes were remade with the new material. The installation required the removal of PMTs at several pass-through points, but was accomplished successfully, as shown in Fig. 5.

Other detector improvements include repairs of PMTs and electronics channels. This ongoing activity will allow the recovery of many PMTs that failed during the SNO data-taking, so that the expected number of working PMTs for SNO+ is about 9000. A new trigger and DAQ system have been implemented, in order to be able to cope with the significant increase in analog sum pulse charges and data volume, because of the higher yield of scintillation with respect to Cherenkov light.

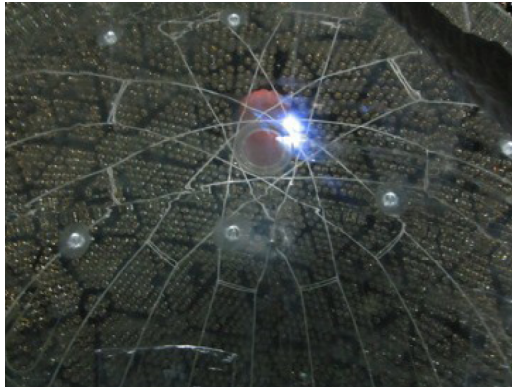


Figure 5. Photo of the hold-down rope net system installed over the AV, taken in January 2012.

3.3. Calibration system

At the energies of pep/CNO solar neutrinos, and the ^{150}Nd Q-value, the radiopurity requirements are much more stringent than in SNO. The calibration source deployment system was completely rebuilt to be fully sealed, following vacuum standards, to avoid any Radon contamination. Even when not in use, the sources themselves are kept in a separate storage box with the same tightness standards. Care had to be taken to ensure mechanical integrity in the case of quick pressure changes, as can frequently happen in an active mine.

In order to cover the lower energy range, different radioactivity sources exist or are being developed: AmBe (n, γ), ^{16}N (γ), ^{24}Na (γ), ^{48}Sc (γ), $^{57,60}\text{Co}$ (γ), ^nNa (γ), ^{90}Y (β).

Additional deployed sources include a scintillator-compatible version of the light diffusor source ("laserball") previously used in SNO, and a Cherenkov source, in which electrons from the β decay of ^8Li cross a spherical shell of UV-transparent acrylic, in order to produce a well-known number of Cherenkov photons and calibrate the light detection efficiency.

A new source-location system was implemented, based on a redundant set of six high resolution cameras mounted on the PSUP. The precise location of the source will be carried out by reconstructing the position of LEDs attached to the source body.

However, due to the stringent radiopurity requirements, calibrations with internally deployed sources will not be possible with the same high frequency that was employed in SNO (monthly). So, in order to calibrate the PMTs and monitor the stability of the scintillator transparency, external light injection systems were designed, based on optical fibers transporting pulses from LEDs or lasers. Two of these systems use a few quartz optical fibers, with narrow beams, and aim at the measurement of the scattering length of the scintillator – by comparing light observed in the direct path with other angles – and at the monitoring of the scintillator attenuation stability.

The PMT calibration system will use LED light pulses conveyed to all PMTs, by means of ~ 100 1 mm PMMA fiber cables (each with 2 fibers for redundancy), in order to carry out the timing and the gain calibration of the PMT. The fibers are mounted in uniformly distributed positions in the PSUP, directing their beams inward, across the AV and hitting the PMTs on the opposite side. The choice of 1 mm PMMA fibers allows a good coupling to the LEDs, and ensures that the beams coming out of each fiber are wide enough to illuminate about 200 PMTs, thus ensuring that all PMTs are illuminated redundantly. However, fibers with a large numerical aperture have a higher time dispersion, that was measured for all fibers in the quality control before installation. The results are presented in Fig. 6, and show that most present pulses with a width of about 4 ns (including the LED pulse dispersion), which is enough for the synchronization of the PMTs to 1 ns (for which many pulses are accumulated).

All the fibers have now been brought into the detector, and one-third of them (in the positions accessible from the bottom) have been installed in their final mount place. The remaining two-thirds will be installed in 2013 by boat. A full detector dry-run was taken in the fall of 2012,

in order to test the PMTs, the HV system, the DAQ and the calibration systems, as well as the offline data processing setup. All the PMTs were turned on with HV, and the electronics and DAQ demonstrated a very good performance. In addition, all the installed fibers were illuminated with LEDs, and detector data taken in that configuration. Figure 7 shows a display of the integrated number of counts over a run taken with one of the fibers, in which the cluster of PMTs illuminated by direct and reflected light is clearly seen.

4. Status and expected schedule

The schedule of the experiment is the following. In the spring of 2013, the water fill will start, and during that operation, the remaining fibers, PMTs and location cameras will be installed. Once the detector is full, a calibration campaign will allow the characterization of the detector, especially the PMTs. The replacement of water by the LAB will follow and the first scintillator data is expected in 2014.

Acknowledgments

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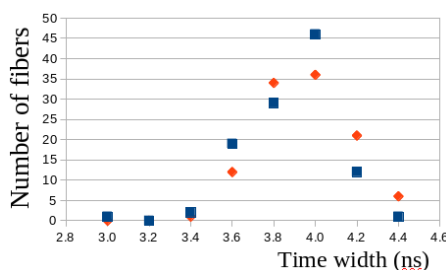


Figure 6. Results of timing spread quality control tests of the optical fibers for the PMT calibration system.

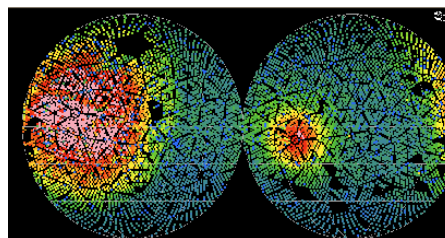


Figure 7. Display of accumulated events over test runs of the PMT calibration system. Color code: Red/pink means a high number of counts, while green/blue means a small number.

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